

Innovative approaches to sediment management

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Sedimentation close to dams in large and deep reservoirs is mainly related to sediment transport by turbidity currents. The state of the art regarding the management of turbidity currents is presented here, and illustrated with two case studies. Possible solutions, such as the development of physical obstacles and the evacuation of sediments from water intake structures, are proposed.

Turbidity currents can transport fine materials in relatively high concentrations over long distances along the reservoir bottom and down to the deepest point in the lake, which is usually close to the dam and outlet works. There, the transported sediments will normally settle. Sediment deposition in reservoirs not only reduces storage capacity, but also increases the risk of blockage at intake structures.

1. Sedimentation

1.1 Reservoir sedimentation

Sedimentation is a subject of major importance in reservoirs worldwide and is, in large and deep reservoirs, mainly related to the phenomenon of sediment transport by turbidity currents [De Cesare, 1998¹, De Cesare *et al.*, 2001², Schleiss *et al.*, 2010³]. The construction of a large dam significantly modifies the flow regime of natural streams in the artificial lake and downstream. Considering the usually high sediment concentrations during flood events, the inflow shows a greater density than the ambient fluid. Suspended load can therefore be entrained along the reservoir bottom all the way down to the dam as turbidity currents. These currents can, when strong enough, erode and transport considerable sediment volumes within the reservoir itself. As a consequence, material deposits may rapidly cover the bottom outlet, affect the operation of the power intake and reduce the storage capacity of the reservoir.

Although the aim behind the efforts to create reservoirs is to store water, part of the solid material carried along by the inflow is usually deposited within the reservoir. Dam construction can considerably alter the flow behaviour from fluvial to lacustrine, with deposition of incoming solid particles. A reservoir, like a natural lake, can silt up at various rates [Basson, 2009⁴]. In extreme cases, reservoirs may become completely filled with sediments within just a few years. A reservoir can only be sustainable or represent a renewable

source of energy when sedimentation is controlled through adequate management, for which suitable measures should be devised [Schleiss and Oehy, 2002⁵].

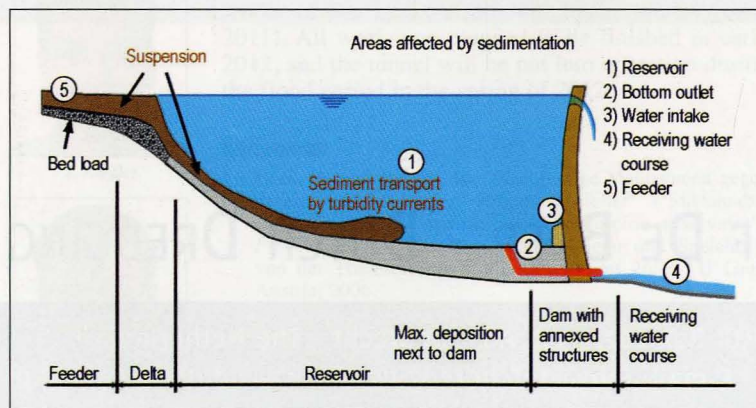
Studies of sedimentation problems have led to many achievements in knowledge in the past years and decades [De Cesare and Lafitte, 2007⁶]. However, although the issue is not new, its importance is still widely underestimated and often given insufficient attention. Studies which started in the late 1980s led to a much broader view on the transportation and other processes of sedimentation. Improved simulation techniques, applicable both in the laboratory and numerical models, have allowed for further insights on turbidity currents which, since the end of the 1990s, have been identified as the major medium for moving sediments within large and deep reservoirs. During this period, the notion of sustainability started to become more prominent within ecological related topics. More recently, efforts have been made to find long-term solutions for reservoir sedimentation problems.

1.2 Turbidity currents

The erosion of soil within a catchment area and in the riverbed is the origin of most sediment material transported by a river. The erosion process normally starts in the high mountainous regions, continues in the highlands and plains, and ends in the lakes or in the sea as sediments. Depending on the sediment supply from the watershed and the flow intensity in terms of velocity and turbulence, rivers usually carry sediment particles of a range of sizes. During flood events the fraction of fine sediments may reach some 80 to 90 per cent of the total sediment carried by the river, and the total sediment discharge is usually significant. If the suspended sediment concentration is high enough it may become a turbidity current.

Turbidity currents are a type of sediment gravity current whereby flows of water laden with sediments move down slopes in otherwise still water (Fig. 1). Their driving force is gained from the suspended matter (fine solid material), which renders the flowing turbid water heavier than the clear water above. When a sediment-laden river enters a large reservoir, the coarser particles deposit gradually and form a delta in the headwater area of the reservoir that extends further into the reservoir as deposition continues. Finer particles, being suspended, flow through the delta stream and pass the lip point of the delta. If, after the lip point of the delta, the difference in density between the clear lake water and inflowing water is high enough, it may cause the flow to plunge and turbidity currents can be induced. On its path within the reservoir, the turbidity current may unload or even re-suspend granular material. Subsequently, the sediments are deposited along

Fig. 1. Schematic drawing of sediment transport by a turbidity current inside a reservoir, the type of sediment deposits and affected areas.



the path as a result of the decreased flow velocity caused by an increased cross-sectional area. Fine sediments (clay and silt fractions) are usually the only particles that remain in suspension long enough. They follow over long distances along the reservoir bottom along the thalweg, through the impoundment and down to the deepest point in the lake, which is usually near the dam outlet. Once at the dam, the sediment-laden waters form a muddy layer and settle.

1.3 Measures against reservoir sedimentation

Several measures against reservoir sedimentation have been proposed. However not all of them are sustainable, efficient and affordable [Fan and Morris, 1997⁷, Alam, 1999⁸, and Batuca and Jordaan 2000⁹]. As an example, the heightening of dams and outlet works provides only a short-term solution.

There is a strong need to limit sediment accumulation in reservoirs to ensure their sustainable use. Management of sedimentation in Alpine reservoirs cannot be achieved by a standard generalized rule or procedure. Furthermore, sediment management is not limited to the reservoir itself, as it begins in the catchment areas and extends to the downstream river. Every situation has to be analysed individually to determine the best combination of solutions to be applied. The possible measures are summarized in Fig. 2 and grouped according to the areas where they can be applied.

An integrated approach to sediment management that includes all feasible strategies is required to balance the sediment budget across reservoirs. Integrated sediment management includes an analysis of the complete sediment problem and applies the range of sediment strategies appropriate to the site. This approach implies that schemes must be operated in a manner that is consistent with the preservation of sustainable long-term benefits.

A sustainable sedimentation strategy should also encompass the downstream reaches and monitoring data should include downstream impacts as well as sedimentation processes in the reservoir.

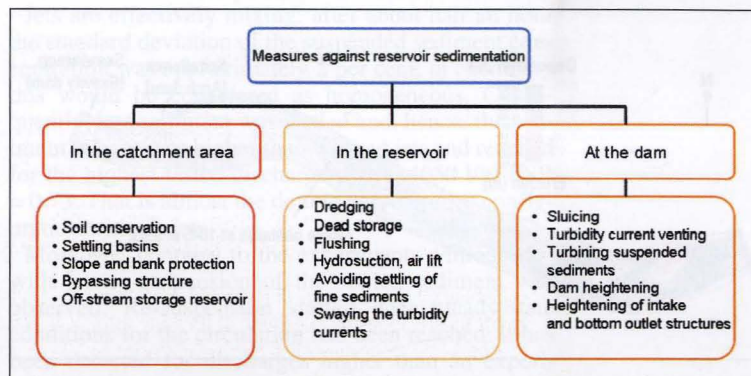
2. Case studies

Two examples are presented to illustrate both the diversity and similarities of different schemes and the methods adopted to solve sedimentation problems. Both reservoirs are located in the Swiss Alps, at the Grimsel reservoir in the Bernese Oberland and Luzonne in Ticino (see Fig. 3).

The reservoirs are at similar altitudes and have comparable storage volumes. The Grimsel reservoir has its normal water level at el. 1908 and Luzzone at el. 1606. Their storage volumes are $101 \times 10^6 \text{ m}^3$ and $108 \times 10^6 \text{ m}^3$, respectively.

2.1 Grimsel reservoir, the use of submerged dams

This ongoing project consists of heightening, by 23 m, the two existing dams which form the Grimsel reservoir. The excavation and demolition works necessary for the planned heightening will generate approximately $150\,000 \text{ m}^3$ of crushed concrete material. This large amount of material will be stored somewhere near the construction site. The idea of building some kind of obstacle in the form of a submerged embankment dam arose from the desire to prevent sediment deposition from turbidity currents in the area near the intake structures (Fig. 4). The occurrence and impact of turbidity currents on reservoir sedimentation were



investigated and the efficiency of such submerged obstacles on sediment retention was confirmed.

The reservoir is approximately 5.5 km long and 300 m wide. The depth is regularly increasing from the inflow to the middle of the lake where a narrow canyon exists. The intake and bottom outlet structures are located in the deepest area, approximately 90 m deep, downstream of the canyon.

Numerical simulations of a typical flood event revealed that a turbidity current develops and propagates to the deepest area of the reservoir close to the dam [Oehy and Schleiss, 2001¹⁰]. During such an event, considerable sediment deposits are created in the area of the intake and bottom outlet structures. Upstream of the deepest part of the reservoir, the canyon with a negative slope causes a slowing down of the current so that sedimentation occurs.

Two possible configurations for obstacles were numerically evaluated [Oehy 2003¹¹, Oehy and Schleiss 2007¹²]. The first configuration consisted of a single embankment dam, 15 m high and 150 m long, located upstream of the canyon in a counter-slope of the lake. The second configuration consisted of two submerged embankment dams placed in the middle of the lake, one after each other with a horizontal shift, so that the current needs to flow around or over them. In this case, the two dams would be 10 m high and 210 m long. Both configurations do not extend over the whole width of the valley so as to keep a free passage

Fig. 2. Catalogue of possible measures for reservoir sediment management [Schleiss and Oehy 2002⁵].



Fig. 3: Location and pictures of the two Swiss dams and reservoirs investigated. (Map: Swiss Committee on Dams; Grimsel photo: Michael Müller, Luzzone photo: Andres Fankhauser)

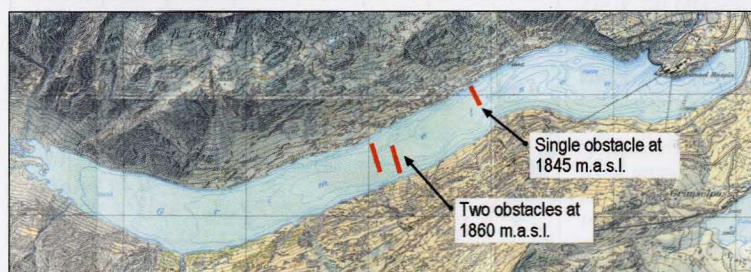


Fig. 4. Position of investigated submerged dams as possible obstacles to turbidity currents in the Grimsel reservoir.

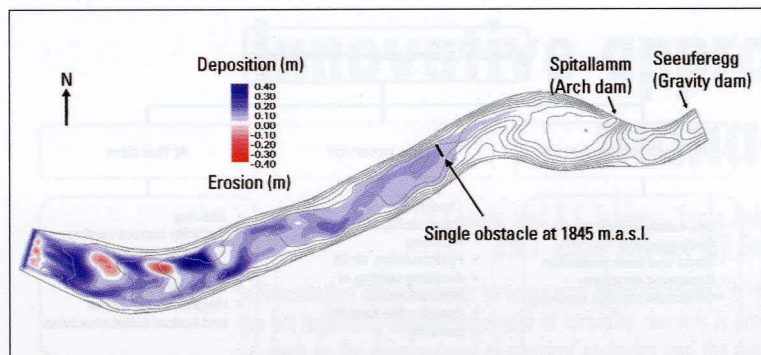


Fig. 5. Potential sediment deposits after flood induced turbidity current blocked by a submerged embankment dam in the Grimsel reservoir.

for water flow during the emptying of the reservoir. The obstacle clearly blocks the flow and reflects the major part of the turbidity current while some of the fluid of the turbidity current flows over the obstacle. As a consequence, a considerable amount of sediment deposits occur upstream of the obstacle (Fig. 5).

Results of an investigation into the effects of an embankment dam, built from the demolition and excavation materials created from the heightening of the Grimsel dams, were consistent with physical experiments. Findings indicated that the height should be at least twice the height of the approaching turbidity current to block the flow efficiently. A 15 m height of the dam was sufficient and ensures that the elevation of the dam crest is below the minimum operating level of the reservoir. It is estimated that the retention of sediments behind the dam lasts for at least 20 to 50 years.

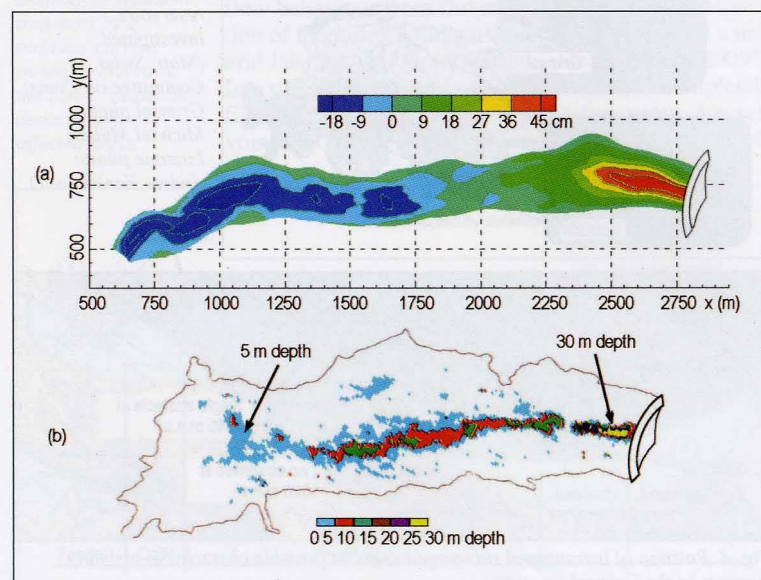
It can be concluded that the recycling of the demolition and excavation materials to build a submerged embankment dam is an excellent opportunity to control reservoir sedimentation caused by turbidity currents.

2.2 Sedimentation in the Luzzone reservoir: venting of the turbidity currents

The Luzzone arch dam of the Blenio Hydropower Company (OFIBLE) was built between 1958 and 1963 near the village of Olivone in the southern part of Switzerland. The maximum crest height is 208 m and the crown is 530 m long.

Turbidity current flow in a laboratory flume as well as field measurements during two summer seasons at the Luzzone reservoir were used to validate a 3D

Fig. 6. Calculated sediment depth change caused by a flood induced strong turbidity current event on the bottom of the reservoir. (a), measured magnitude of sediment deposits after 31 years in service; (b), the location of major sedimentary deposits close to the dam is clearly confirmed.



numerical model [De Cesare, 1998¹]. User-defined erosion and deposition modules that take into account the interaction between the current and the existing sediment deposits were programmed to simulate the balance between sediment deposition and erosion in the model.

The initial geometry of the reservoir, in its deeper part, is characterized by a V-shaped valley that has accumulated sediments for more than 40 years. The mean bottom width is around 50 m. A trapezoidal section approximately characterizes the reservoir geometry. The bottom shape is nearly symmetrical in the reach near the dam. The average longitudinal slope along the reservoir bottom is about 4 per cent. Major sediment deposits cover approximately 0.1 km² of the lake bottom, or around 8 per cent of the total reservoir surface.

During 1985, the reservoir was completely drawn down, allowing for the release of alluvial deposits through the bottom outlet during free-surface flushing over a period of seven weeks. At present, regular short-term pressure flushing keeps the intake of the bottom outlet free from sediments. Nevertheless, the power intake has recently been raised to minimize potential blockages from sediments.

To clarify the flow mechanism of river-induced turbidity currents in an artificial lake, field observations of turbidity currents were carried out in the reservoir and in its main inflow river. Turbidity currents were simulated numerically with observed boundary conditions and the results were compared with on-site measurements.

The plunging of the tributary occurs just after the inflow into the reservoir. The underflow turbidity current then accelerates downstream along the bed. After about 40 minutes, the current reaches the dam. It is reflected and returns upstream, interacting with the still downstream moving body of the turbidity current. The returning current travels upstream over a distance of about two thirds of the total reservoir length.

The global motion inside the lake becomes insignificant after approximately four hours while sediment inflow stopped after approximately 1.5 hours. A sediment-laden underwater muddy lake is formed, which will then settle its granular material over several hours or even days. As a result of particle entrainment from the existing sediment deposits, concentration increases as the current moves on. The current is globally erosive and thus becomes stronger during its advancing stage. The volume of sediment entrained from the bottom is around 35 000 m³, compared with 9000 m³ contributed by the inflow river.

Fig. 7 shows the location of the global erosion and deposition for the simulated turbidity current, these numerically obtained results were compared with the thickness of sediment deposits over the whole reservoir obtained by bathymetric survey after 31 years of operation.

The numerical model can be used as a strategic evaluation tool for reservoir management to analyse various technical solutions to prevent sedimentation in the most vulnerable parts of the reservoir, the bottom outlet and the water intake. Based on this simulation, the optimal timing of the opening of the bottom outlet can furthermore be determined to release an important part of the sediment yield beyond the dam during floods (venting), hence reducing overall sedimentation.

As a first measure, the already partially sediment-covered water intake has been heightened to ensure its functioning. This has been done some years after the

dam heightening to 17 m. Sediment samples and their characteristics showed that it is still possible to perform successful pressure flushing, but long-term strategic decisions have to be taken within the next few years to ensure that the power intake is operational for a long time. Local sediment removal and the provision of a geo-textile screen between the bottom outlet and the water intake together with turbidity current venting may lead to a sustainable solution.

3. Sediment evacuation through intakes by jet-induced flow

3.1 Innovative approach to evacuate fine sediment

Motivated by the problem of reservoir sedimentation, an experimental study was launched with the aim of developing an alternative efficient method to release sediment from a reservoir. The concept is based on the release of sediment through the headrace tunnel and turbines whereby a special focus was set on the fine sediment in the area upstream of the power intakes. Specific jet arrangements should provide the energy and generate the optimal circulation needed to maintain the sediment in suspension and enhance its entrainment into the power intakes during turbinning sequences.

3.2 Experimental set-up and main results

This new idea was experimentally tested in a rectangular laboratory tank 2 m wide, 1.5 m high and 4 m long. A circular jet configuration with four jets arranged in a circle on a horizontal plane was systematically investigated. The influence of the jet characteristics (nozzle diameter d_j , jet velocity v_j , jet discharge Q_j , and jet angle θ) and the geometrical configuration parameters on the sediment release was investigated.

As an initial condition, an almost homogeneous sediment concentration distribution was induced by air bubbles. This condition simulated a muddy layer as would form in front of a dam by the fading of a turbidity current. The water level during all the experiments was held constant by releasing the same discharge through the water intake as was introduced by the jets (experiments with jets) or through the back wall (experiments without jets), respectively. Turbidity measurements combined with flow velocity measurements gave information about the sediment release efficiency.

The sediment release (evacuated sediment ratio, ESR) is defined as the evacuated sediment weight P_{out} divided by the sediment weight initially supplied P_{in} and represents the normalized temporal integral of the released sediment amount: $ESR = P_{out}/P_{in}$. Analogously, the settled sediment ratio is the settled sediment divided by the sediment weight initially supplied P_{in} .

Experiments without jets as reference configuration showed an almost linear relationship between the sediment release and the discharge within the tested range: the higher the discharge, the higher the evacuated sediment ratio. For a constant discharge, the ultimate sediment release as well as the settled sediment ratio was easily estimated by a simple physical approach, taking into account the settling velocity and the flow field generated by the discharge through the water intake and the back wall. For the tested discharge range the sediment release was between 0.09 and 0.37 for reference configuration.

Jets are effectively mixing: after about half an hour the standard deviation of the suspended sediment concentration was approximately 5 per cent; in chemistry this would be considered as homogeneous. Consequently, less sediment was settled and, hence, the sediment release was higher than without jets and reached for the highest tested discharge ($\Sigma Q_j = 4050$ l/h) ESR = 0.73. That is almost the double the reference configuration without jets.

Moreover, contrary to the experiments without jets, with jets re-suspension of the settled sediment was observed. Re-suspension started once steady-state conditions for the circulation had been reached. It has been detected for discharges higher than an experimentally determined threshold. The observed evolution of the re-suspension rate suggests that for times much longer than the residence time all of the initially supplied sediment can be evacuated.

The normalized optimal geometrical parameter combination was determined as follows: off-bottom clearance of the jet arrangement $C/B = 0.175$, water intake height $h_i/B = 0.25$, distance of the jet arrangement to the front wall $d_{axis}/B = 0.525$, distance between two neighbouring jets $l_j/B = 0.15$, jet angle $\theta = 0^\circ$ and water height in the tank $h/B = 0.6$. In optimum conditions and with the highest tested jet discharge ($\Sigma Q_j = 4050$ l/h) after four hours a sediment release of ESR = 0.73 was achieved. Without jets and with the same discharge through the water intake the sediment release reached ESR = 0.37.

The corresponding flow pattern was similar to an axial mixer, which in the literature is reported as favourable for suspension.

The efficiency of the jets was established by comparing the sediment release obtained in different conditions: once when jets were employed, once without jets. The predicted efficiency based on time and discharge independent empirical relationships is around 1.7 for the optimum jet configuration. Using the measured data the efficiency depends on discharge and increases with time (Fig. 8). At the end of the transient phase and when re-suspension started the efficiency

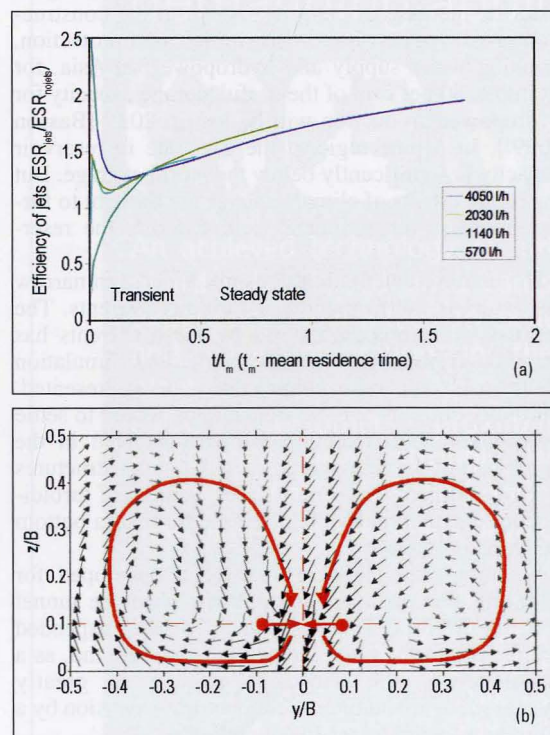


Fig. 7. (a) Efficiency of jets by comparing the evacuated sediment ratio obtained with and without jets, respectively; (b) Axial propeller type flow pattern in the transversal plane for water intake height $h_i/B = 0.25$ and off-bottom clearance $C/B = 0.1$.

was approximately 1.5. With the highest tested discharge, the efficiency reached after four hours (equals approximately $1.7 \tau_m$, τ_m being mean residence time) almost 2 ($\Sigma Q_i = 4050 \text{ l/h}$).

Because of the fine grain size used in the experiments (mean diameter of 60 μm) the application focuses on large reservoirs where the sediment is well sized along the thalweg and only fine particles are expected in front of the dam as it is the case for sediments transported by turbidity currents.

In the case study of Mauvoisin with a 250 m-high dam in Switzerland creating a large reservoir, a first attempt was made to scale up the research results. Based on the available discharge and head of the existing water transfer tunnel, a preliminary optimal circular jet arrangement was suggested. Even though tests at a natural scale had not yet been performed, it is expected that with a circular jet arrangement definitely more sediment could be evacuated than without jets. Moreover, the sedimentation of the region near the outlet devices could be greatly reduced and their clogging could be avoided.

An economic study revealed that a jet arrangement is a low cost installation which, based on the performed experiments, is essential when aiming for high sediment release and counteracting reservoir sedimentation.

4. Conclusions and outlook

Even if the reasons for, and processes involved in, reservoir sedimentation have been well known for some time, sustainable and preventive measures are rarely taken into consideration in the design of new reservoirs. To avoid operational problems in powerhouses, sedimentation is often addressed at existing reservoirs with measures which are only efficient for a limited time. Since most measures will lose their effect within a short period of time, the sustainable operation of reservoirs and the production of valuable peak energy can thus be endangered.

The current worldwide annual mean loss of storage capacity as a result of sedimentation is already higher than the increase of capacity thanks to the construction of new reservoirs for irrigation, flood protection, drinking water supply and hydropower. In Asia, for example, 80 per cent of the useful storage capacity for hydropower production will be lost in 2035 [Basson 2009⁴]. In Alpine regions, the loss rate in reservoir capacity is significantly below the world average. But the future effects of climate change are thought to further increase the sediment yield entering the reservoirs.

The main sedimentation transport process in narrow reservoirs is the formation of turbidity currents. The sedimentation process caused by these currents has been described here and the numerical simulation results of some case studies have been presented. Turbidity currents may be stopped and forced to settle down their solid load by obstacles situated in the upper part of the reservoir to keep the outlet structures free of sediments. In certain cases, venting of turbidity currents, that means their release through a bottom outlet, is possible.

An innovative technique has been developed for releasing fine sediment through the headrace tunnel and the turbines. The entrainment of the suspended sediment into the power intake is enhanced and, as a consequence, the sediment release is greatly increased, by maintaining sediment in suspension by a jet induced axial mixer-like circulation.

The reservoirs taken as examples in this paper have similar altitudes and volumes; the diversity of the watershed (especially the part covered by glacier) and the reservoir characteristics explain the differences in sedimentation rates and the variety of applicable and appropriate measures to be taken against reservoir sedimentation. From these case studies it can be concluded that a combination of several measures might provide the best solution. The experimental results of the new method for releasing sediment through the water intake are very promising even though no tests at natural scale were performed so far. \diamond

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